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Hyperbolic Direction Finding with Sferics of Transatlantic Origin

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Abstract. The described AFCRC experimental 'hyperbolic direction finder' consists of an array of sferic receivers in the New England area, connected by wide-band data links so that microsecond differences in pulse arrival time can be measured. The hyperbolic directions can be determined from the time differences.

In a series of coordinated runs, individual sferics originating in western Europe were observed by both the New England net and the sferics net of the British Meteorological Office. The BMO furnished the geographic coordinates of the lightning strokes so that measurements of position could be compared. Tabulated results for 150 sferics show an average absolute deviation from the mean of only 31 nautical miles.

Introduction. Natural radio noise in the 3- to 30-kc/s (VLF) band consists of impulses (sferics) caused by electrical activity in the earth's atmosphere. The peak power radiated from some lightning strokes approaches the order of 1 million megawatts. Because of generally good propagation in the VLF band, these sferics are receivable at tremendous distances from their sources. Aside from their importance to an understanding of the lightning mechanism, sferics provide rich sources of signals for studies in radio propagation, and they are useful in locating electrical storms for meteorologic purposes. Individual lightning strokes can be located by triangulation, from bearings supplied by a number of geographically separated observation stations equipped with direction finders. Conventional sferic nets use direction finders of the type first described by *Watson-Watt* [1926], in which the magnetic components of sferics are resolved by mutually perpendicular loop antennas, and displayed on a cathode-ray-tube screen in such a way that the direction of the source is electronically indicated, almost instantaneously.

The Watson-Watt type of direction finder suffers from three major defects: siting errors, errors in instrumental accuracy, and polarization errors. The first two can presumably be eliminated, or calibrated out. The polarization errors, ascribed to the effects of downcoming skywaves that have undergone a rotation of polarization, are fundamentally more difficult to cope with. These waves induce unwanted voltages in the loop antennas, causing the cathode-ray-tube display to be either indeterminate or erroneous.

The new type of instrumentation described in this report locates sferics by timing their arrival rather than by resolving magnetic-field components. The results should therefore be relatively free of polarization errors.

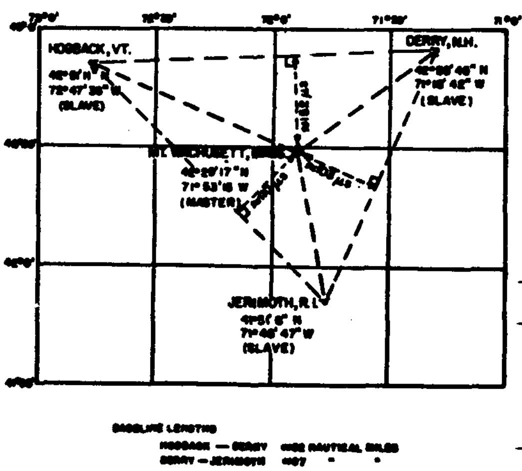

Fig. 1. Station configuration.

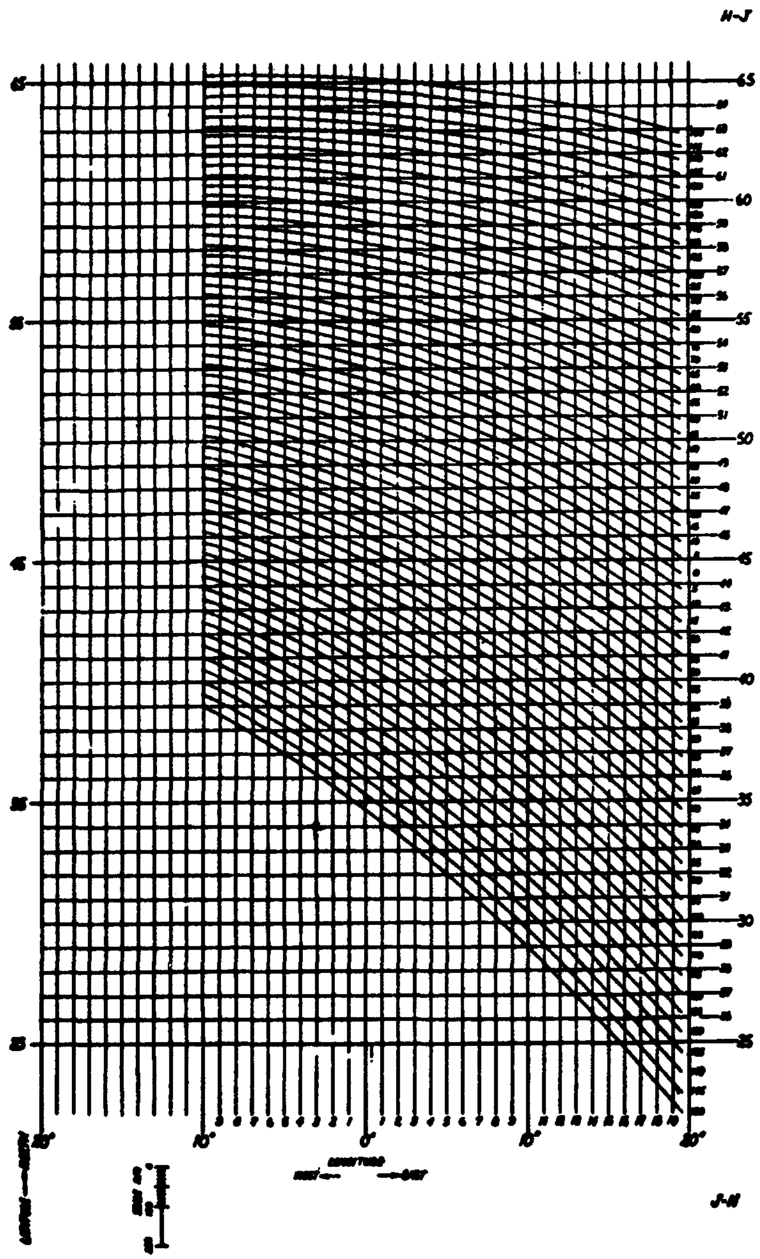

Fig. 2. Isochrons for western Europe.

At moderate distances there is the possibility of proving and calibrating the time-of-arrival net by means of artificial sferics generated by a new technique [*Newman*, 1957; *Lewis*, 1958], but these are probably too weak for testing at intercontinental ranges. In the present experiment, use was made of natural sferics occurring within the local coverage area of the sferic net of the British Meteorological Office [*World Meteorological Organization*, 1955]. This net, which employs the cross-loop technique, provided the fix coordinates of the individual lightnings,

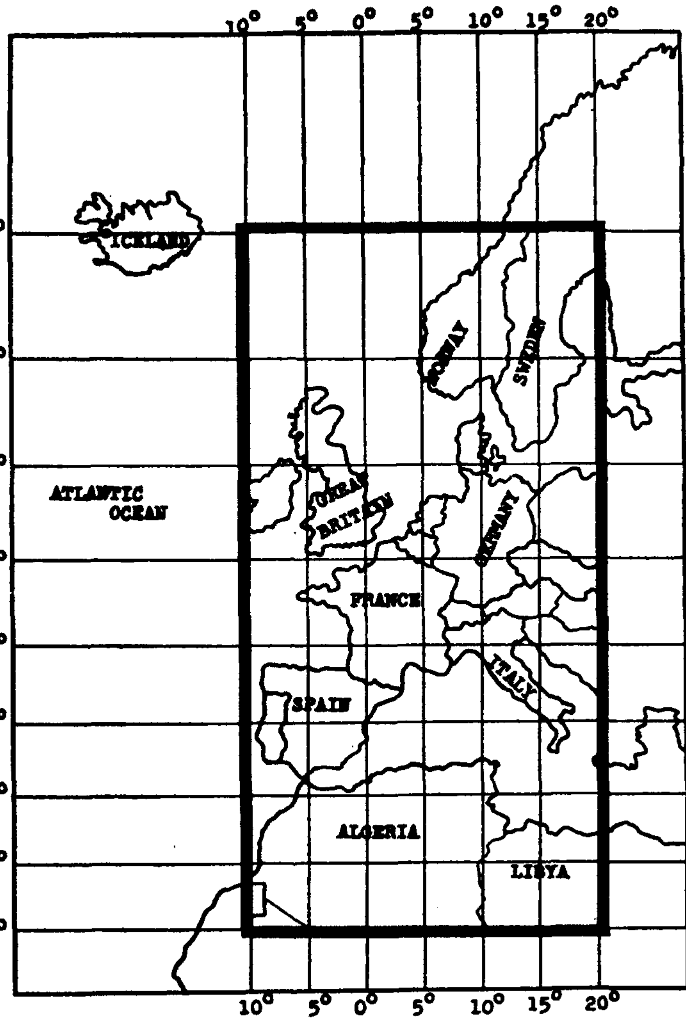

Fig. 3. Area covered by the isochrons in Figure 2.

against which the AFCRC positional data were compared. Fixes were reported to the nearest 0.5° of latitude and of longitude. This is somewhat equivalent to the nearest 30 nautical miles in north-south position and the nearest 18.5 miles in east-west position. Because the AFCRC net lies more or less due west of Europe, the time differences measured by AFCRC are relatively insensitive to the east-west position of the lightning stroke but quite sensitive to its north-south position.

General Description of the hyperbolic direction finder. The AFCRC hyperbolic direction finder consists of an array of four stations arranged as shown in Figure 1. The three stations at the apexes of the triangle, namely those at Hogback, Jerimoth, and Derry, are similar unmanned stations, each of which has two functions: (1) to receive the VLF sferic pulses on a vertical antenna, and (2) to relay the received VLF signals continuously over a microwave link to the master station on Mt. Wachusett. At the master station four VLF signals are available, the one received directly at the master station, and a relayed signal from each of the three slaves. At the master, the sferic pulses are displayed on oscilloscopes and photographed on continuously moving 35-mm film. (See Appendix A.) When studying long-range sferics from approximately the same direction only two slave

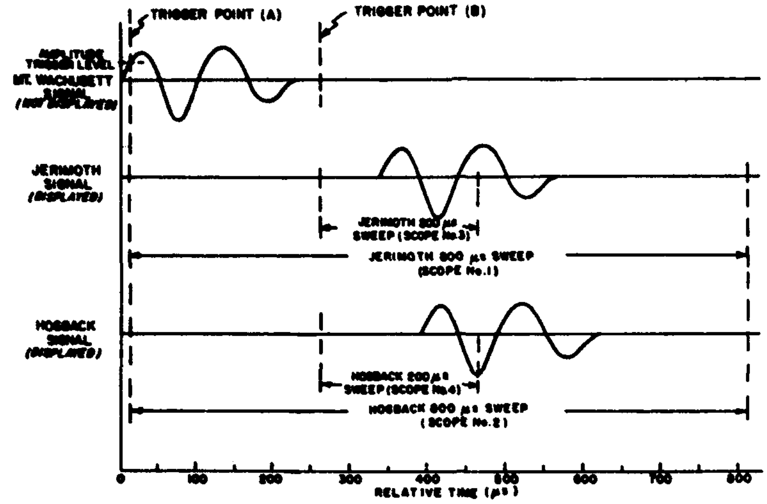

Fig. 4. Sequence of events at master station (Mt. Wachusett).

signals are needed. The signals used are from the pair of slaves whose base line is most nearly at right angles to the direction of interest. Since there are three slaves, there is always at least one suitable pair, no matter what the direction of interest is. In the transatlantic sferics experiment, the Hogback-Jerimoth pair was appropriate.

The pulses as received at Hogback and Jerimoth, after being delayed known amounts by traveling over the microwave links, were recorded at the master station along with time markers. The original difference in arrival time of the sferic wave at Hogback and at Jerimoth could be deduced from the photographic film. From this information a line of position for the lightning stroke was determined.

For constant-velocity radio waves on a plane earth, the locus of a pulse source that gives a constant difference in arrival time at two slaves is a hyperbola. On a curved earth the curves of equal time difference (isochrons) involve geodesics, and are best calculated with the aid of electronic computers. (At ranges large compared with base-line length, and neglecting the earth's ellipticity and wave-propagation anomalies, the isochrons approximate great circles.) The isochrons shown in Figure 2, obtained in this way, include allowance for the ellipticity of the earth. (See Appendix B.) (These curves are similar to those used in Loran navigati :ı, and, in fact, the arrival-time technique is commonly called *Inverse* Loran—inverse in the sense that the roles of the receivers and transmitters are interchanged.) In Figure 2 the lines of latitude and longitude are represented as orthogonal straight lines, and the linear degree scales have been adjusted so that relative distances are approximately preserved. The isochrons are drawn with 5-µsec intervals, convenient for interpolation, 1 µsec corresponding to a displacement of about 6 nautical miles. The approximate geographic area covered is shown framed in Figure 3.

The isochrons in Figure 2 permit determination of *lines of position* only. If there were a second net similar to the New England net, say in Alaska, the isochrons from this would intersect with those in Figure 2 and permit actual fixes to be obtained.

To understand the action of the AFCRC net, suppose that a sferic originates from the northeast somewhere on the zero isochron, thus arriving exactly simultaneously at Hogback and Jerimoth. Reference to Figure 1 will show that the master station receives the sferic directly about 110 µsec before it arrives at Hogback and Jerimoth. After leaving Hogback, the microwave signal arrives at the master station 284 µsec later. The corresponding delay for Jerimoth is 239 µsec. The sequence of events at the *master station* is illustrated in Figure 4, where the Wachusett signal is shown beginning at time

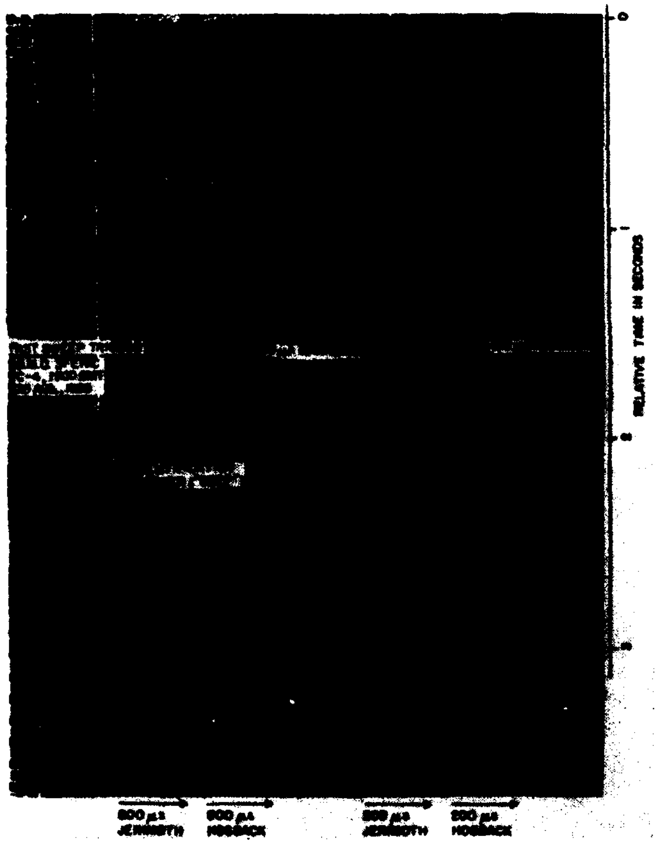

Fig. 5. Typical film record.

zero. About 349 μsec later the relayed signal from Jerimoth arrives, and 394 μsec later the relayed signal from Hogback arrives.

Shortly after the direct signal begins at Wachusett, its instantaneous amplitude exceeds an arbitrary threshold level at time A, Figure 4. This instant is not a critical one in the time measurement, but is used to switch on the beams of oscilloscopes 1 and 2 (see Fig. 6), and to initiate their 800-μsec sweeps. When the relayed pulse from Jerimoth arrives at 349 μsec, it is displayed on scope 1, the 800-μsec sweeps being already under way. Similarly, the Hogback signal is displayed on scope 2. These displays are for the purpose of recording the whole waveforms but are too slow to permit accurate time resolution.

At the instant A, Figure 4, a phantastron circuit is also initiated. After an adjustable delay (in this case about 250 μsec), this circuit puts a marker tick on each of the slow sweeps, simultaneously brightens the beams on scopes 3 and 4, and triggers the 200-μsec sweeps. These fast sweeps display the beginnings of the sferics with sufficient time resolution to permit the precision time-difference measurement. If the source of the sferic had been south of the zero isochron, the signal relayed by Jerimoth would have arrived sooner, and that from Hogback later, than the time shown in Figure 4. (To make it possible

Fig. 6. Orientation of the oscilloscopes.

to center the fast sweep on the beginning of sferics from any arbitrary direction, two independently variable phantastrons are provided, one for each slave, both being initiated at time *A*. This feature was not needed and was not used in the present experiment.)

The sweeps shown in Figure 6 are imaged by the open camera lens onto 35-mm film, driven at a uniform but adjustable speed. In the absence of deflecting signals the sweeps would appear on the film as almost horizontal lines, since the sweep velocity is many times greater than the film velocity. Figure 5 is an enlargement of a section of 35-mm film showing sferic waveforms on the four data scopes. An identification marker put on by the small time and identification scope is also shown along the edge. The orientation in Figure 6 is the same as in Figure 5.

Every 10 μsec, a sharp timing-mark pulse from a stable oscillator is simultaneously fed into both the fast-sweep oscilloscopes, every tenth or 100-μsec mark being accentuated. These markers, which can be seen in Figure 6, provide the essential scale for the precision time measurement, in a way completely independent of the accuracy of sweep initiation, sweep linearity, and so forth.

The difference in time of arrival of the relayed pulses at the master station is *measured* from the photographic records of the fast trace. Then, from the known travel times and instrumental delays, the difference in original arrival times at the slaves is *inferred*. This is the time difference for which the isochrons (Fig. 2) are computed.

Figure 2 shows only small portions of the isochrons. If these were actually continued back toward the receiving (slave) stations, they would pass between them and continue on out again. Since a lightning stroke anywhere on an isochron gives the same time difference, this measurement alone cannot indicate on which side of the base line connecting the two slaves the lightning occurred. This ambiguity, however, is easily resolved from information supplied by the master station. In Figure 1, if the sferic came from the southwest limb of the isochron, the relayed pulses from Hogback and Derry would have arrived only slightly (about 130 μsec) after the direct arrival at the master station, instead of about 350 μsec as depicted in Figure 4. The approximate arrival sequence of relayed signals from Hogback and Jerimoth, relative to the direct arrival at the Mt. Wachusett master station, is shown in Figure 7 for all azimuths. In this figure slight departures from symmetry are caused by the fact that the net geometry itself is not quite symmetrical. The optimum pair of slaves to use in monitoring any desired direction is shown in Figure 8, along with the approximate time differences at the slaves, for sferics of distant origin.

During the transatlantic runs, each sferic above a preset level at the master triggered the sweeps, regardless of the direction of interest. Of course many of the sweeps were blank or did not contain a matchable portion of the pulse, since for their direction the phantastron delays were not appropriate. In a more refined system a series of gates could be designed so that those unwanted sferics would not register at all, leaving the film record uncluttered.

Factors affecting accuracy. The precision of

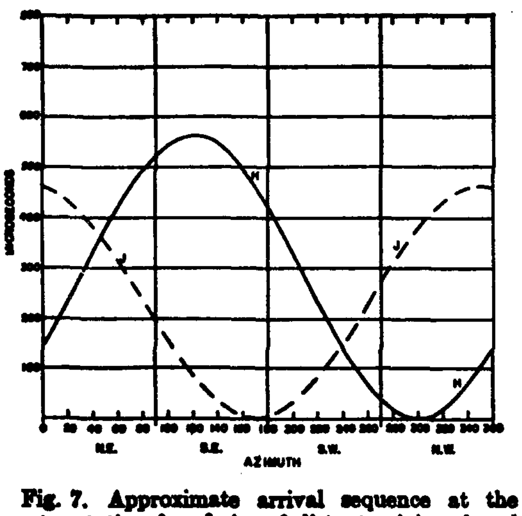

Fig. 7. Approximate arrival sequence at the master station for sferics of distant origin relayed by Hogback and Jerimoth.

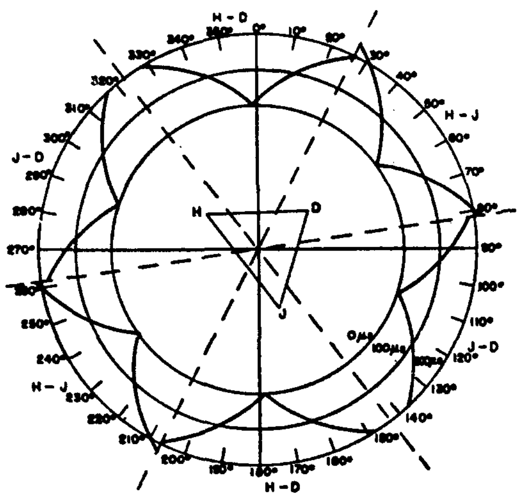

Fig. 8. Approximate time differences and optimum sectors.

phase measurement depends on just how similar the recorded pulses from the two slaves are, and this in turn depends on a number of factors that can be roughly grouped into three categories: propagation effects, noise, and instrumentation. In designing a time-difference system, the first objective is to make the instrumentation errors negligibly small in comparison with the propagation and noise errors, which are of natural origin and harder to eliminate.

For this reason the receiving antennas and their siting should be as similar as possible at all slave stations, and the associated amplifiers and other units should be as nearly identical as possible so that modifications of the pulse, if any, will be similar. There is a question of what bandwidth to use in the data channels. If very narrow bandwidths are used, the resulting quasi-cycles will *appear* nearly identical, but narrowing the bandwidth increases the susceptibility to slight changes in the electrical components and makes recognition of corresponding cycles more difficult. In designing the equipment it was the policy to make the data bandwidth broad (4–45 kc/s), leaving for future experimentation the problem of assessing the advantages, if any, of decreasing the bandwidth.

At first sight it might appear that, if the time-difference measurement is to be made to the order of a microsecond, a data-channel bandwidth of the order of a megacycle would be required. This, however, is not the case, since in principle two narrow-band impulses can be matched to any desired degree of accuracy, *provided that they are absolutely identical,* and provided that there is sufficient structural detail in the pulses to permit recognition of corresponding cycles. In the AFCRC apparatus the 800-μsec sweeps that display all the pulses are used to ensure that the correct cycles are chosen from the fast sweeps that usually display only part of the waveform.

In the case of the VLF sferic pulses received from a distance of several thousand miles, the filtering effects of the propagation path combine with the source spectrum of the sferic to result in a quasi-sinusoidal waveform of quasi-frequency of the order of 15 kc/s and quasi-period of about 70 μsec. Thus, if time differences are to be measured to a precision of 1 μsec, this amounts to measuring the relative quasi-phases of the pulses to about 1.4 per cent of a cycle, or 5°.

The components of the microwave circuit are very broad-band (6 Mc/s), and the delay differences in the equipment are very small (order of 0.05 μsec), so that slight changes in the operating voltages should not contribute appreciably to the error.

The propagation time from slave to master may be expected to vary somewhat with the refractive conditions in the atmosphere. Since the index of refraction of air in the region close to the ground is of the order of $n = 1 + (300 \times 10^{-6})$, it is unlikely that changes in n could cause the transit time along a straight path to vary more than a few hundredths of a microsecond. The increase in path length due to bending of the rays should not amount to more than a few tenths of a microsecond over the 50-mile links, even assuming angular deviations greater than any considered by *Wong* [1958]. (Occasional amplitude changes of the received signal

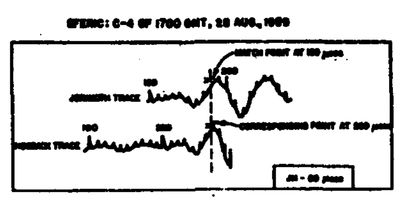

Fig. 9. Illustration of phase matching.

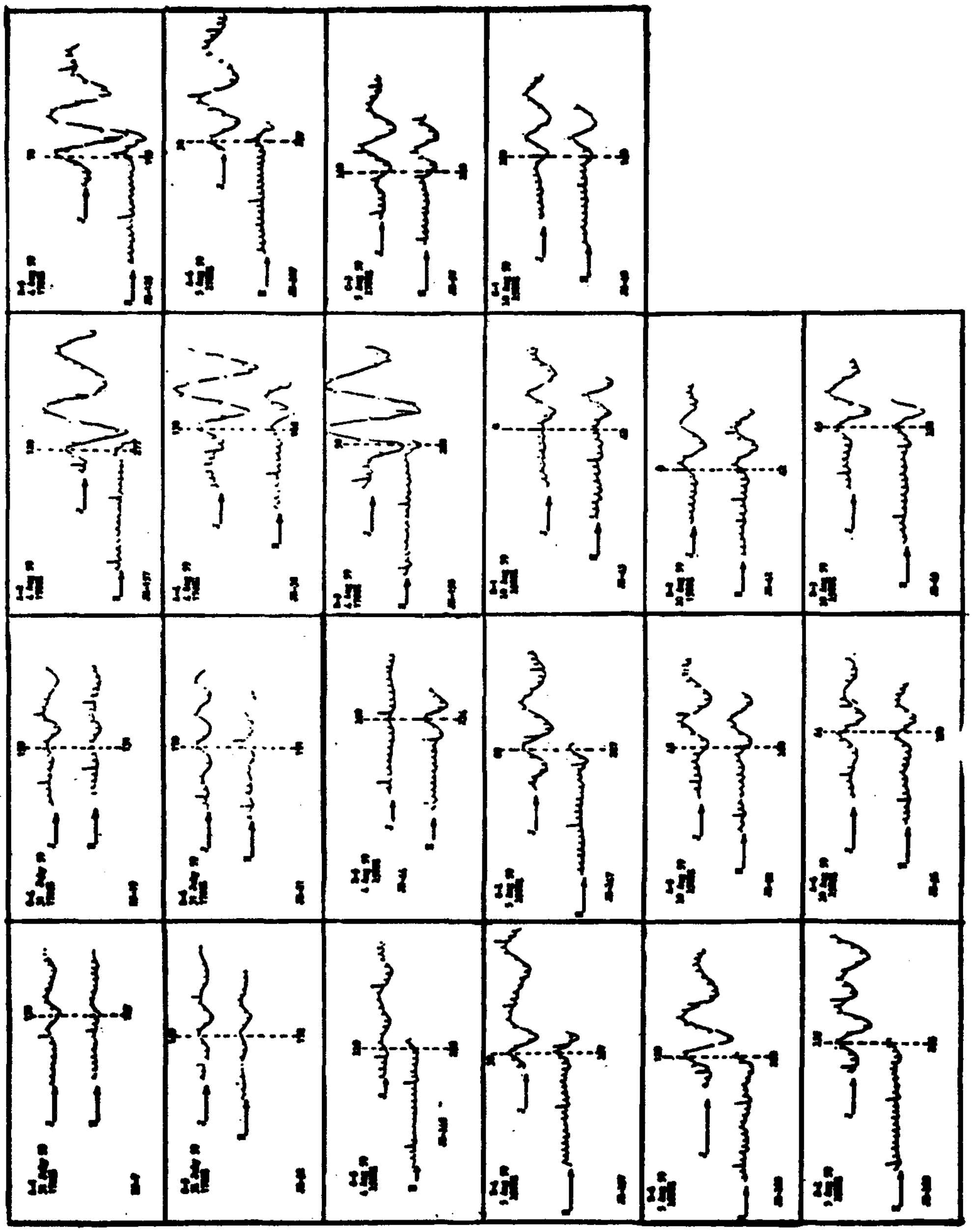

Fig. 10. Traces used for time-difference measurement (July 31 to Aug. 10).

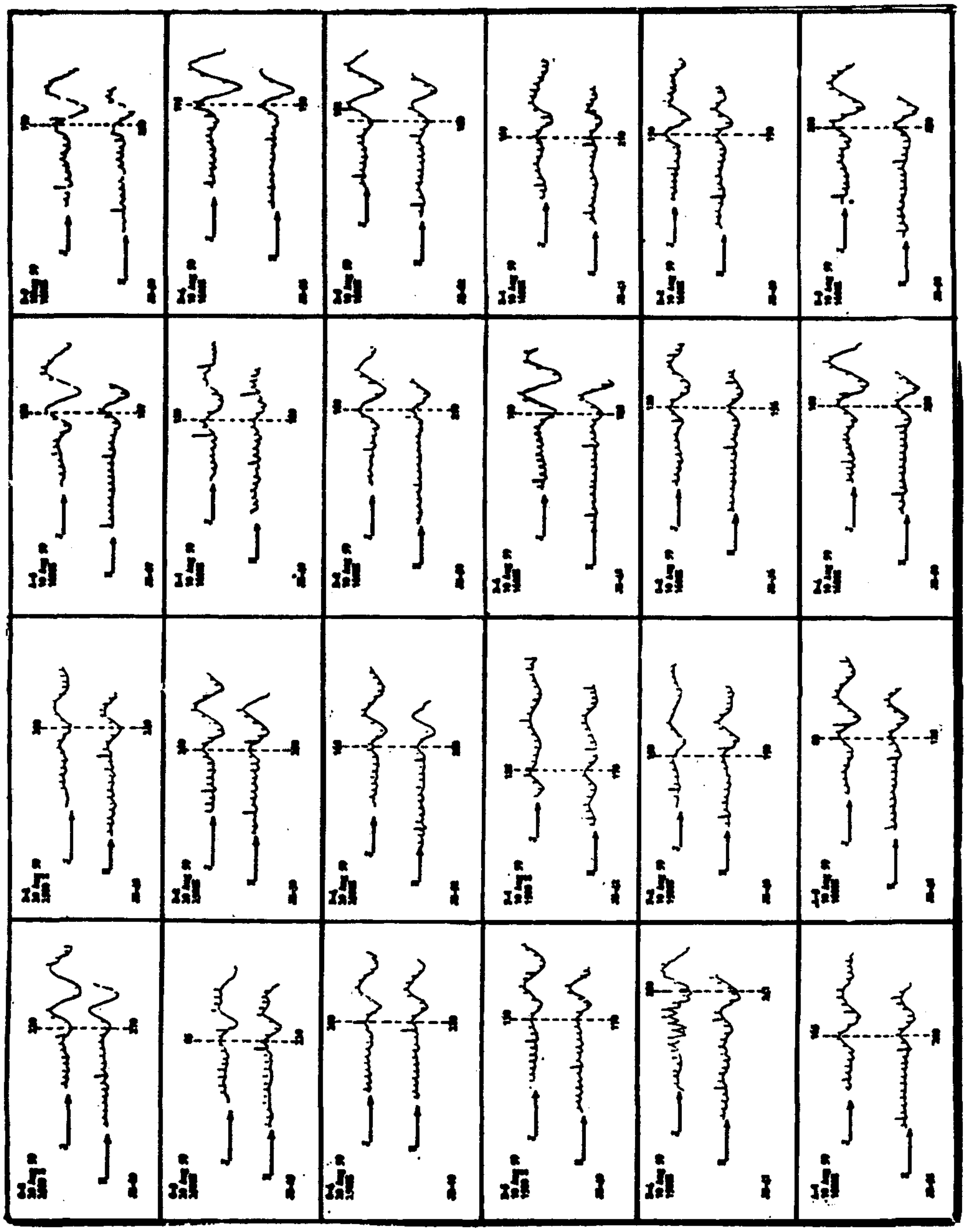

Fig. 11. Traces used for time-difference measurement (Aug 10, 1500Z–1600Z).

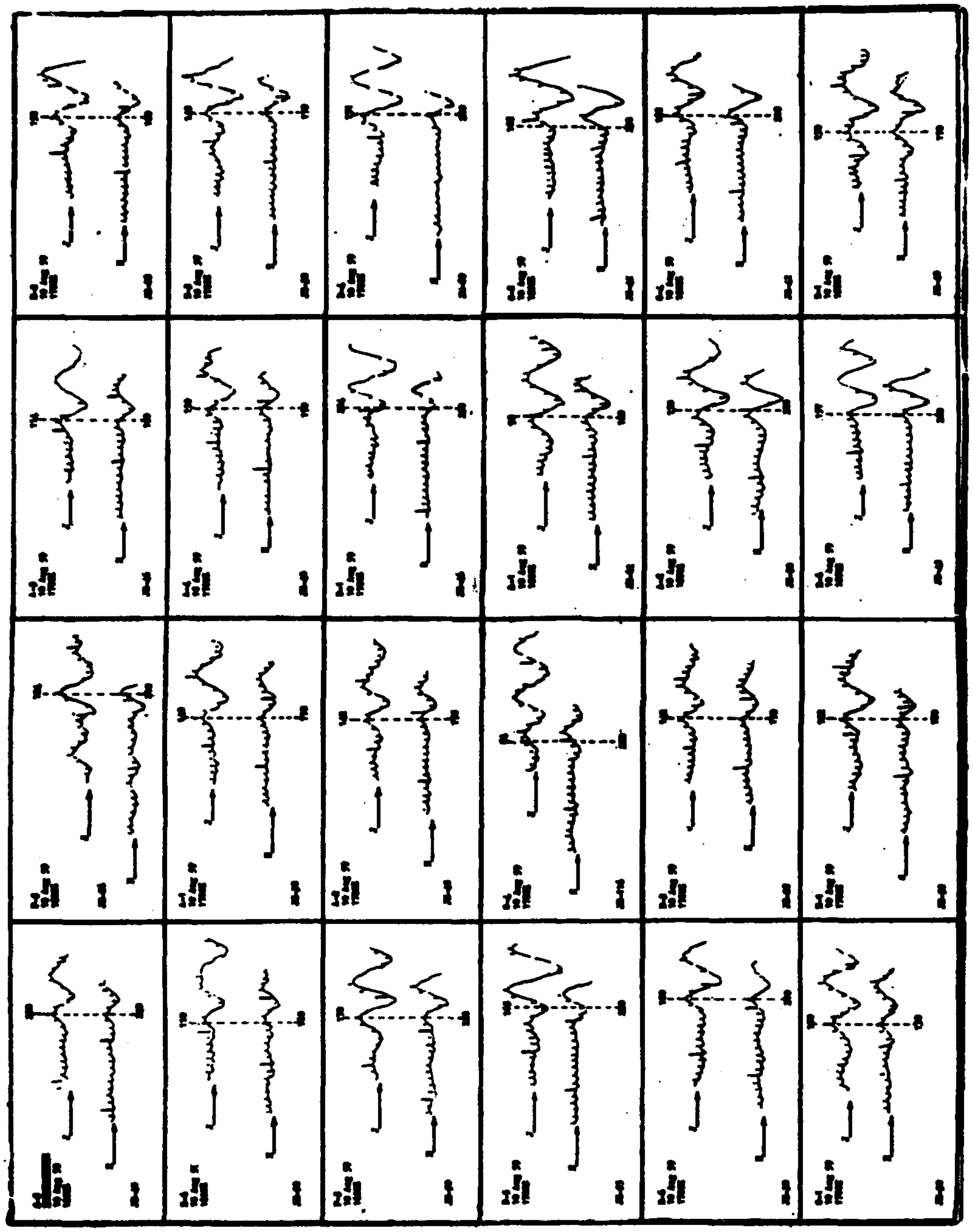

Fig. 12. Traces used for time-difference measurement (Aug. 10, 1600Z–1800Z).

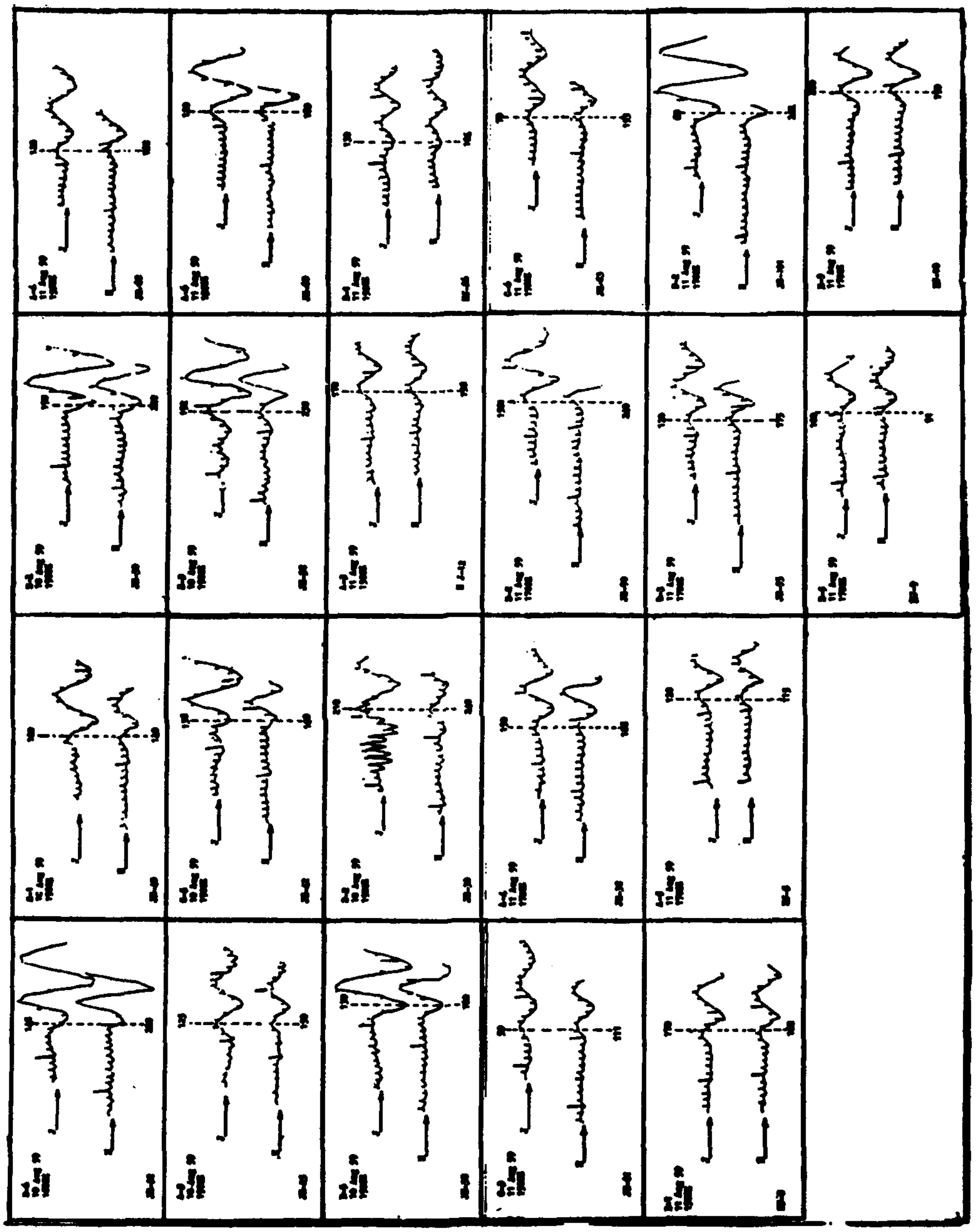

Fig. 13. Traces used for time-difference measurement (Aug. 10, 1800Z, to Aug. 11, 1700Z).

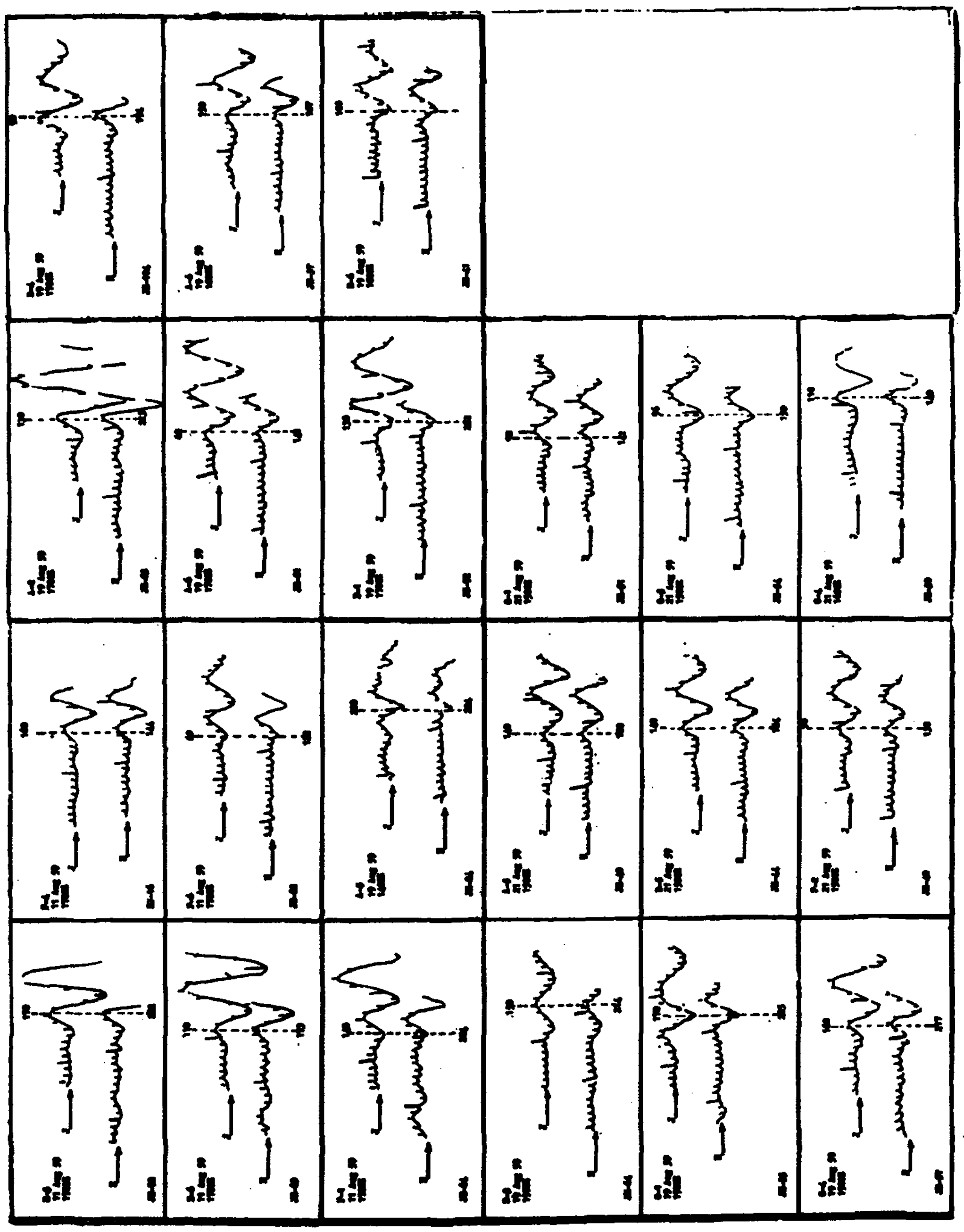

Fig. 14. Traces used for time-difference measurement (Aug. 11, 1700Z, to Aug. 21, 1600Z).

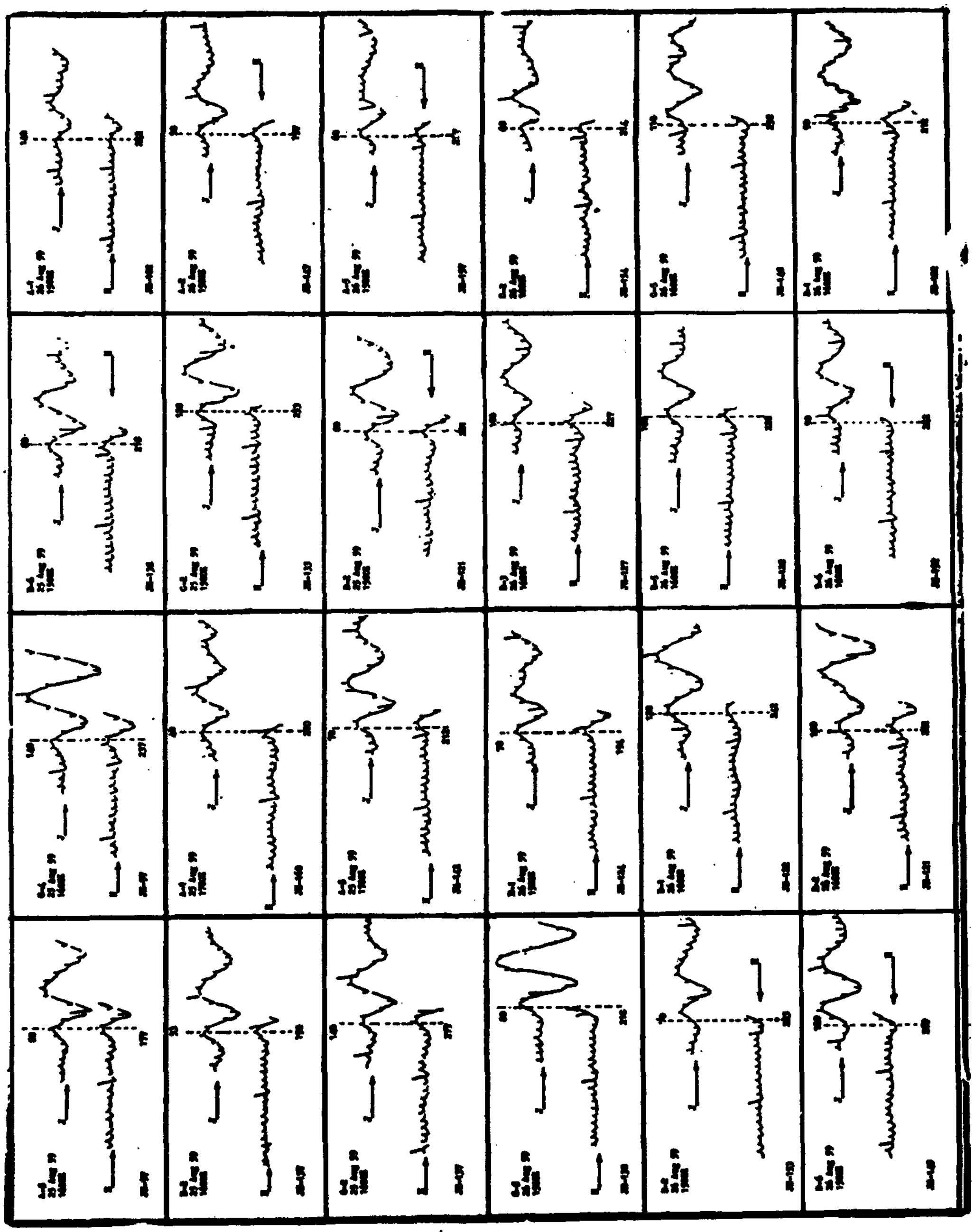

Fig. 15. Traces used for time-difference measurement (Aug. 25–26).

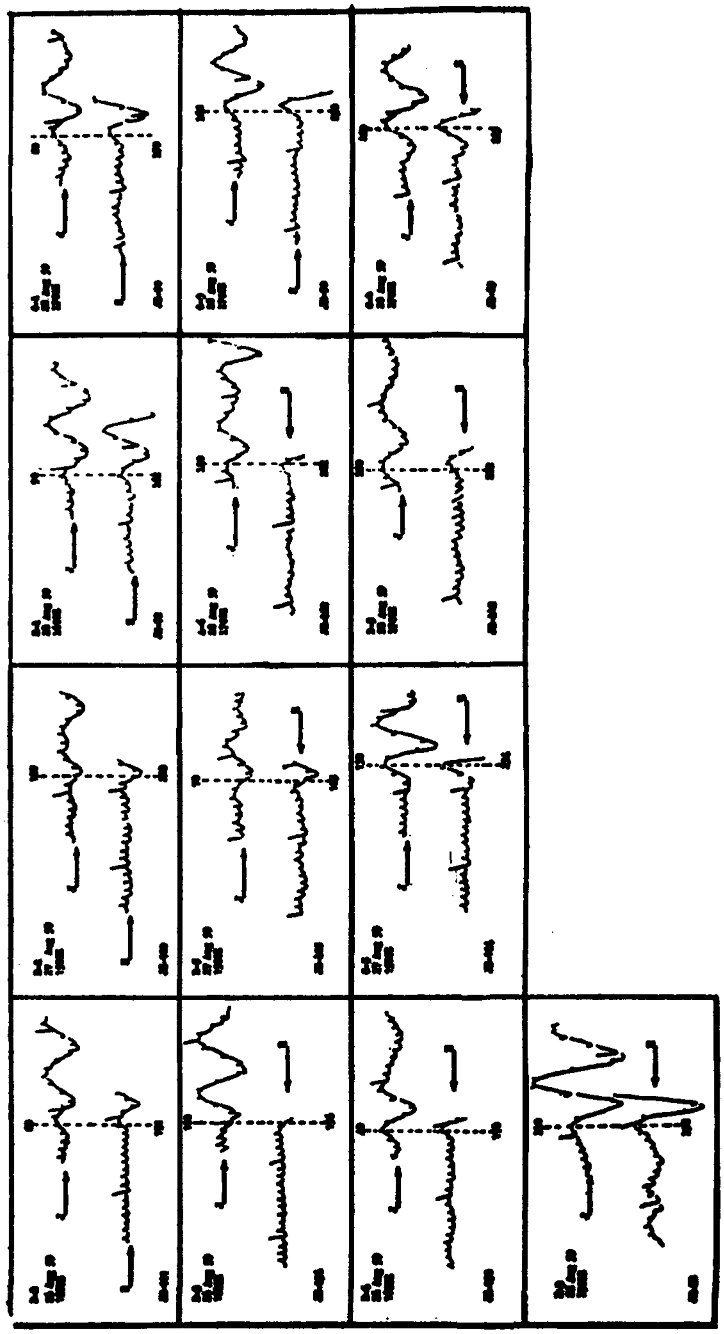

Fig. 16. Traces used for time-difference measurement (Aug. 26–28).

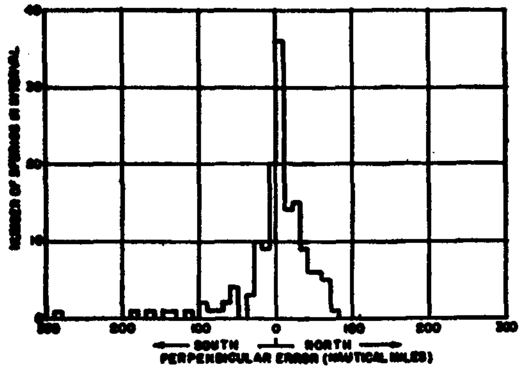

Fig. 17. Distribution of errors.

are observed, but when the microwave installation and adjustments are correct, no fades severe enough to take the signal out of the FM limiting range have been observed with this equipment.)

The waveform display is another possible source of instrumental error. Since the 10-μsec time markers are applied directly, sweep linearity is not a major source of error, but the cathode-ray-tube trace has a finite spot size, and in the present equipment the injection of the time markers causes a slight distortion of the trace due to overshoot of the markers. This contributes to the phase-matching errors, particularly when the sferic deflections are small. Any slight distortions in the amplifiers, modulators, and the scopes themselves as well as image resolution and other photographic matters should be considered.

In general, the sferic signals are fairly large, so that there is little or no difficulty with tube noise. There can be interference from near-by radio-frequency transmitters and high-voltage power lines. Ordinary 60-cycle hum can be reduced to a negligible level by appropriate shielding and filtering. Communications transmitters in the VLF band, such as NSS, for example, radiate in the acceptance band of the apparatus, but usually this makes only a small, inconsequential ripple on the trace or is entirely negligible, depending on the gain setting used. (A ripple from a near-by 100-kc/s Loran-C transmitter can be seen on the early part of the J trace of sferic D-2 of August 10 at 1900 GMT in Fig. 13.)

The most serious form of interference is that caused by other lightning strokes than the ones desired. Since vertical-whip antennas currently used accept sferics from all directions, it must occasionally happen that one of these will arrive simultaneously with the desired sferic pulse and produce a resultant waveform sufficiently distorted to prevent an accurate phase measurement. In the event of a thunderstorm in the immediate area or directly overhead, the vertical antenna can go into a corona-discharge condition that temporarily prevents its use.

Finally, there are errors due to the basic fact that the pulses arrive at the slave stations from slightly different angles with respect to the source. Since the received pulses will therefore not be precisely identical, this constitutes a source of error, the estimation of which requires experimentation. It would seem that, although the received pulses would be more similar if the slave stations were placed close together, there would be a net loss of accuracy due to the concomitant spreading out of the isochron lines.

While recognizing the several sources of individual error, the purpose of the present experiment was to actually operate the net and to determine what the combined errors were.

Fig. 18. External view of typical slave station.

TABLE 1

Date, 1959	Time, GMT	Designation	From Film, μsec	Δt for Slaves	BMO Fix	Perpendicular Error, naut. miles
July 31	1700	A-1	HJ-7	HJ-52	54-1/2N-08 E	5 N
		B-6	JH-21	HJ-24	52 N-05 E	23 N
		C-4	HJ-19	HJ-64	55-1/2N-10 E	2 S
		C-5	JH-32	HJ-13	50-1/2N-06 E	27 N
Aug. 4	1500	C-5	JH-148	JH-103	41 N-01-1/2W	7 S
		E-5	JH-44	HJ-01	46-1/2N-13 E	42 N
Aug. 4	1700	A-2	JH-157	JH-112	39-1/2N-01-1/2W	24 N
		A-4	JH-38	HJ-07	47-1/2N-14 E	9 N
		B-5	JH-125	JH-80	41 N-03 E	60 N
		D-3	JH-150	JH-105	40-1/2N-04 W	60 N
Aug. 5	1700	A-6	JH-167	JH-122	41-1/2N-05 W	66 S
		C-3	JH-50	JH-5	43-1/2N-19 E	27 N
Aug. 5	1800	B-4	JH-157	JH-112	41 N-04-1/2W	2 N
		B-6	JH-160	JH-115	43 N-05 W	115 S
Aug. 5	1900	B-1	JH-160	JH-115	41-1/2N-05 W	32 S
		C-1	JH-147	JH-102	43-1/2N-06-1/2W	40 S
Aug. 10	1500	A-5	JH-52	JH-7	51-1/2N-09-1/2W	30 N
		A-6	JH-36	HJ-9	50-1/2N-05-1/2E	10 N
		B-1	JH-43	HJ-2	51-1/2N-03 E	20 S
		B-2	JH-42	HJ-3	49 N-07 E	30 N
		B-3	JH-63	JH-18	51-1/2N- 1-1/2E	140 S
		C-1	JH-40	HJ-5	49-1/2N-07 E	20 N
		C-2	JH-60	JH-15	47-1/2N-08 E	15 N
		C-3	JH-25	HJ-20	50 N-12 E	0
		C-4	JH-10	HJ-35	51 N-13-1/2E	10 N
		D-1	JH-40	HJ-5	50 N-06 E	0
		D-2	JH-30	HJ-15	51 N-06-1/2E	10 S
		D-4	JH-52	JH-7	47-1/2N-08 E	30 N
		D-5	JH-40	HJ-5	55-1/2N-05 W	170 S
		E-4	JH-41	HJ-4	48-1/2N-08 E	40 N
		F-1	JH-42	HJ-3	49-1/2N-07 E	10 N
		F-2	JH-40	HJ-5	49-1/2N-07 E	20 N
Aug. 10	1600	A-1	JH-55	JH-10	51 N-04 W	2 S
		A-3	JH-48	JH-03	51-1/2N-03-1/2W	5 N
		A-5	JH-67	JH-22	44-1/2N-10-1/2E	60 N
		B-1	JH-40	HJ-05	51 N-03 E	10 S
		B-2	JH-50	JH-05	51 N-02-1/2E	60 S
		B-3	JH-30	HJ-15	51 N-07-1/2E	20 S
		B-4	JH-35	HJ-10	51-1/2N-01-1/2E	10 N
		B-5	JH-62	JH-17	50 N-05 E	100 S
		B-6	JH-48	JH-03	51-1/2N-03-1/2W	0
		C-2	JH-36	HJ-9	51-1/2N- 1-1/2E	20 N
		D-4	JH-50	JH-05	51-1/2N-03-1/2W	10 S
		E-1	JH-41	HJ-04	50 N-06 E	0
		E-2	JH-40	HJ-05	52-1/2N-07-1/2W	20 N
		E-3	JH-50	JH-05	51 N-04-1/2W	30 N
		E-5	JH-40	HJ-05	50-1/2N-03 E	20 N
		E-6	JH-50	JH-05	48 N-08 E	20 N
		F-3	JH-50	JH-05	47-1/2N- 8-1/2E	15 S
		F-5	JH-86	JH-41	46 N-02-1/2E	10 N
Aug. 10	1700	A-1	JH-30	HJ-15	52-1/2N- -1/2E	30 S
		A-2	JH-48	JH-03	48-1/2N- 7-1/2E	26 S
		A-3	JH-46	JH-01	49-1/2N-06 E	5 S
		A-4	JH-40	HJ-05	50 N- 5-1/2E	10 N
		B-1	JH-46	JH-01	49 N- 7-1/2E	0
		B-2	JH-28	HJ-17	52-1/2N- -1/2E	0
		B-3	JH-40	HJ-05	50-1/2N- 6 E	25 S

TABLE 1. Continued

Date, 1959	Time, GMT	Desig-nation	From Film, μsec	Δt for Slaves	BMO Fix	Perpendicular Error, naut. miles
		B-4	JH-69	JH-24	45-1/2N-10-1/2E	18 S
		B-5	JH-55	JH-10	52 N- 8-1/2W	20 S
		B-6	JH-30	HJ-15	52-1/2N- -1/2E	5 S
		C-1	JH-30	HJ-15	51 N- 7 E	5 S
		C-4	JH-116	JH-71	46 N-10 E	30 N
		D-3	JH-28	HJ-17	52-1/2N- -1/2E	5 N
		E-1	JH-58	JH-13	53 N- 7-1/2W	90 S
Aug. 10	1800	A-1	JH-62	JH-17	46 N-10 E	10 N
		A-2	JH-50	JH-05	48 N- 8-1/2E	10 N
		B-6	JH-43	HJ-02	52-1/2N- 8 W	0
		C-2	JH-58	JH-13	51-1/2N- 1 W	20 N
		C-4	JH-42	HJ-03	52 N-00 W	30 S
		D-1	JH-40	HJ-05	52-1/2N- 3 E	100 S
		D-6	JH-52	JH-07	52-1/2N- 9 W	30 S
Aug. 10	1900	A-3	JH-25	HJ-20	51-1/2N- 6-1/2E	2 N
		B-5	JH-30	HJ-15	51 N- 5-1/2E	18 N
		C-1	JH-40	HJ-5	48-1/2N-11 E	2 N
		C-5	JH-42	HJ-3	49-1/2N-07-1/2E	2 N
		D-2	JH-30	HJ-15	51 N-04-1/2E	30 N
		E-1	JH-30	HJ-15	51 N-05-1/2E	15 N
		E-3	JH-38	HJ-7	49 N-07-1/2E	4 N
Aug. 11	1500	A-3	HJ-12	HJ-57	53-1/2N-12-1/2E	18 N
		A-4	JH-68	JH-23	45 N-09 E	50 N
		A-6	JH-60	JH-15	46-1/2N-08-1/2E	35 N
		B-1	HJ-26	HJ-71	56-1/2N-08-1/2E	5 N
		C-3	JH-61	JH-16	46-1/2N-08-1/2E	30 N
		D-1	HJ-08	HJ-53	53 N-14 E	10 N
Aug. 11	1700	A-4	JH-38	HJ-7	48 N-11-1/2E	30 N
		A-5	HJ-5	HJ-50	54 N-11-1/2E	30 S
		B-2	JH-90	JH-45	43-1/2N- 7 E	35 N
		B-3	JH-55	JH-10	46-1/2N-10 E	30 N
		B-5	HJ-9	HJ-54	54 N-11 E	0
		C-6	JH-83	JH-38	44-1/2N- 7 E	25 N
		D-2	JH-101	JH-56	43 N-06 E	30 N
		E-3	HJ-10	HJ-55	54 N-11 E	8 N
		E-5	JH-92	JH-47	43-1/2N- 8 E	2 N
		E-6	JH-63	JH-18	46-1/2N- 9-1/2E	5 S
		F-1	JH-64	JH-19	45 N-11 E	38 N
		F-4	HJ-16	HJ-61	55 N-10-1/2E	6 S
		F-6	JH-62	JH-17	46-1/2N- 9 E	15 N
Aug. 19	1400	A-5	JH-24	HJ-21	48 N-15-1/2E	45 N
Aug. 19	1700	A-2	JH-83	JH-38	46 N- 7 E	52 S
		A-6	JH-81	JH-36	44 N- 8 E	58 N
		B-1	JH-92	JH-47	43 N- 6-1/2E	65 N
		B-4	JH-104	JH-59	42-1/2N- 7 E	2 N
Aug. 19	1800	A-6	JH-37	HJ-8	46-1/2N-13-1/2E	75 N
		B-6	JH-41	HJ-4	46-1/2N-14 E	42 N
Aug. 19	1900	B-3	JH-64	JH-19	46-1/2N-10-1/2E	30 S
		C-1	JH-55	JH-10	47 N-10 E	8 N
		C-4	JH-57	JH-12	47 N-10 E	20 N
Aug. 21	1500	A-5	JH-40	HJ-5	51-1/2N-00 W	5 N
		B-5	JH-44	HJ-1	51-1/2N-00 W	23 S
		F-2	JH-40	HJ-5	51-1/2N-00 W	5 N
		G-1	JH-51	JH-6	51-1/2N-00-1/2W	55 S
		G-3	JH-54	JH-9	49 N-06 E	23 S
Aug. 21	1600	C-4	JH-30	HJ-15	53 N- 1 W	15 S
Aug. 25	1500	B-6	JH-138	JH-93	42 N-01-1/2W	5 S

TABLE 1. Concluded

Date, 1959	Time, GMT	Designation	From Film, μsec	Δt for Slaves	BMO Fix	Perpendicular Error, naut. miles
		C-2	JH-133	JH-88	42 N-01 E	23 S
		D-2	JH-121	JH-76	42-1/2N-00-1/2E	32 N
Aug. 25	1600	A-5	JH-97	JH-52	42 N- 7-1/2E	65 N
		B-2	JH-137	JH-92	42 N- 1-1/2W	6 N
		C-2	JH-137	JH-92	42 N- 1-1/2W	6 N
		C-4	JH-97	JH-52	43 N- 7-1/2E	14 N
Aug. 25	1700	A-1	JH-160	JH-115	41 N-02 W	60 S
		A-5	JH-142	JH-97	43 N- 4-1/2E	190 S
Aug. 26	1500	A-1	JH-102	JH-57	44 N-05 E	16 S
		A-2	JH-147	JH-102	43 N-07 W	5 S
		A-5	JH-157	JH-112	42-1/2N- 7-1/2E	290 S
		C-5	JH-130	JH-85	43-1/2N-00 W	70 S
		D-2	JH-153	JH-108	42-1/2N- 7 W	12 S
		D-6	JH-149	JH-104	42-1/2N- 7 W	7 N
		E-1	JH-124	JH-79	42 N- 0-1/2W	10 N
Aug. 26	1600	B-1	JH-122	JH-77	43-1/2N- 0-1/2W	4 S
		B-2	JH-121	JH-76	42-1/2N- 0-1/2E	35 N
		B-3	JH-127	JH-82	41-1/2N-00 E	65 N
		B-5	JH-128	JH-83	42-1/2N-00	0
		B-6	JH-152	JH-107	42-1/2N-08 W	10 N
		C-2	JH-154	JH-109	41-1/2N- 7-1/2W	42 N
		C-5	JH-148	JH-103	43 N- 7-1/2W	5 S
		D-1	JH-122	JH-77	42 N- 0-1/2E	60 N
		D-2	JH-111	JH-66	42-1/2N- 3-1/2E	38 N
		D-3	JH-156	JH-111	42 N-08 W	15 N
		D-6	JH-150	JH-105	41-1/2N- 7-1/2W	65 N
Aug. 27	1500	D-2	JH-100	JH-55	45 N-01 E	10 N
		B-5	JH-105	JH-60	44 N-04 E	20 S
		C-5	JH-104	JH-59	44 N-03 E	6 N
Aug. 28	1600	E-1	JH-72	JH-27	45 N-09-1/2E	20 N
Aug. 28	1700	A-6	JH-162	JH-117	45 N-10-1/2W	145 S
		B-3	JH-142	JH-97	44 N- 6-1/2W	39 S
		C-1	JH-90	JH-45	43-1/2N-07 E	38 N
		C-3	JH-90	JH-45	44-1/2N-03-1/2E	54 N
		C-4	JH-89	JH-44	43-1/2N-07 E	40 N
		E-3	JH-88	JH-43	43 N-07-1/2E	63 N

Statistically the errors should have a fixed component (bias error) and a random component (scatter error). If truly constant, the bias error would be relatively unimportant since corrections could be made for it.

The sferics experiment. During July and August 1959 the experimental AFCRC time-difference net was operated whenever possible, concurrently with the scheduled runs of the British Meteorological Office net. These runs, each 10 minutes long, immediately preceded each hour, the first run ending at 1300 and the last at 2100 GMT. During these runs only those sferics automatically selected by the Dunstable, England, station had their locations determined. When a certain one was selected, Dunstable sent out a beep to the several direction-finding stations in the United Kingdom by land line.

Upon receipt of the beep, the operators at the BMO stations manually read the bearings of the flashes from a line-and-scale device attached to their cathode-ray tubes, and reported the data to Dunstable. There, the bearings were plotted on a map, and, from the intersection obtained, the fix coordinates were read off. A table of each day's fixes was prepared and mailed to AFCRC, where the time-difference data were processed and analyzed.

The purpose of the beep is to ensure that all operators observe the same sferic. In order

Fig. 19. Internal view of typical slave station.

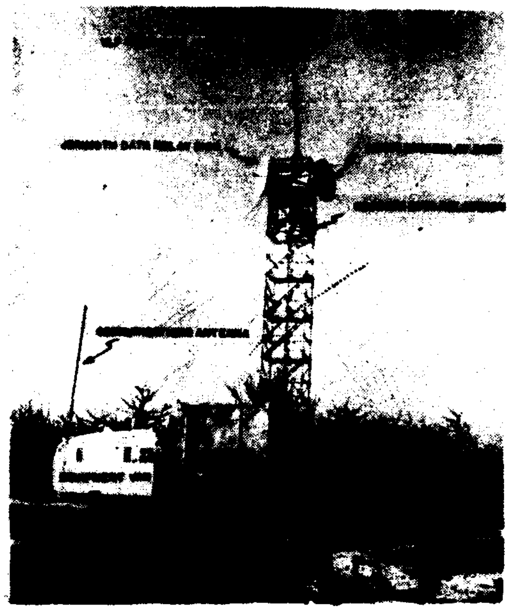

Fig. 20. External view of Mt. Wachusett master station.

Fig. 21. Master station relay racks.

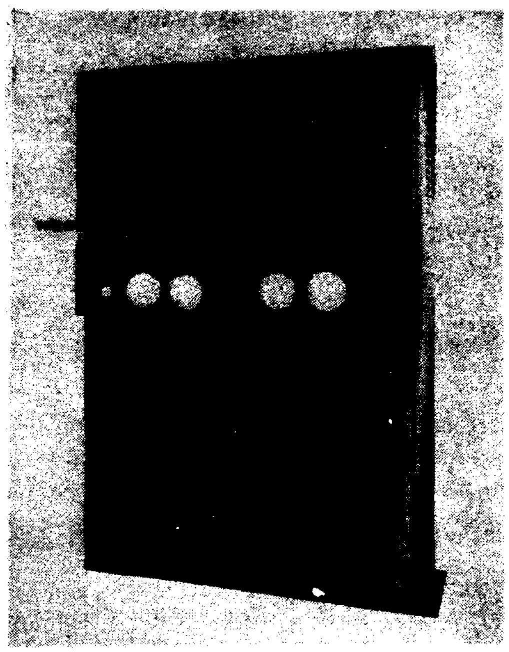

Fig. 22. Master station display unit.

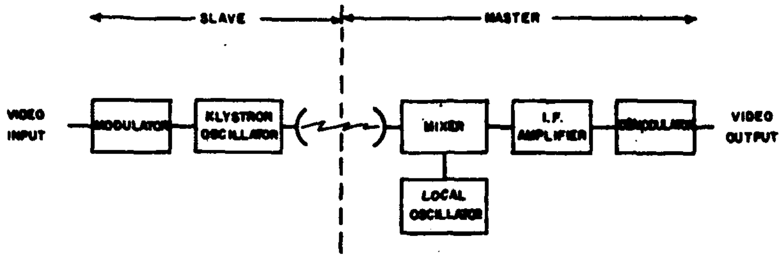

Fig. 23. Block diagram of KTR-1000A microwave equipment.

to avoid confusion when sferic rates are high, and to allow time for reading and reporting, there is a nominal dead time of about 7 seconds before the Dunstable apparatus is ready to select another sferic. Every sixth beep is made extra long, thus dividing the sferics into groups of six. In this way, if one short beep were lost, only some of the individual sferics within that group would be unidentifiable, and the whole run would not be thrown out of register.

In order to ensure that the AFCRC net could unambiguously identify the same individual sferics chosen at Dunstable, that station transmitted the beeps by short-wave radio to America, on 5.045, 12.231, and 15.505 Mc/s, as a special service for this experiment. These beeps were received at the Mt. Wachusett master station and displayed directly on the small time-and-identification oscilloscope (Fig. 6) so that they could be photographed on the same 35-mm film as the sferics traces. The movement of the film, transverse to the beep deflection on the scope, produced the typical indication shown in Figure 5. Owing to the relative position of the cathode-ray tubes, circuit delays, and so forth, the beep always appears on the film delayed by about 0.13 sec from the corresponding sferic.

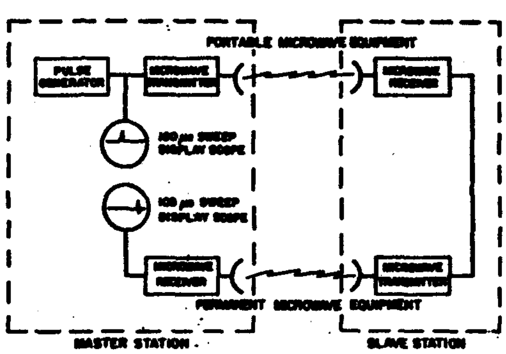

Fig. 24. Round-trip transmission-time measurement.

Data reduction and results. The various steps in analyzing the AFCRC film for each run were, in order, as follows:

(*a*) Identify the beep groups, and the individual beeps.

(*b*) Identify the corresponding sferics, noting those that appeared clearly and with an amplitude suitable for a time measurement.

(*c*) Note whether the list from the BMO gave fixes for the sferics selected in (*b*), and, if so,

(*d*) Carefully trace the waveforms and time markers from a projected image of the film, and label the traces.

(*e*) Phase-match the traced sferics, and read off the time difference for each case, as discussed below.

(*f*) Correct the time difference for slave-to-master travel times, to obtain the actual time difference at the slaves.

(*g*) On a large plotting map of which Figure 2 is a small-scale copy, trace the measured isochron for each sferic, interpolating as required.

(*h*) Plot the position of the sferic as reported by the BMO.

(*i*) Measure the shortest (perpendicular) distance from the fix to the isochron, noting whether the isochron fell north or south of the fix position.

(*j*) Average the results from all sferics to obtain a *mean relative error.*

(*k*) Compute the average absolute deviation from the mean.

The method of phase measurement is illustrated in Figure 9, which shows the traces from the 200-μsec sweeps for sferic C-4 on August 28, 1959, between 1650 and 1700 GMT. (The

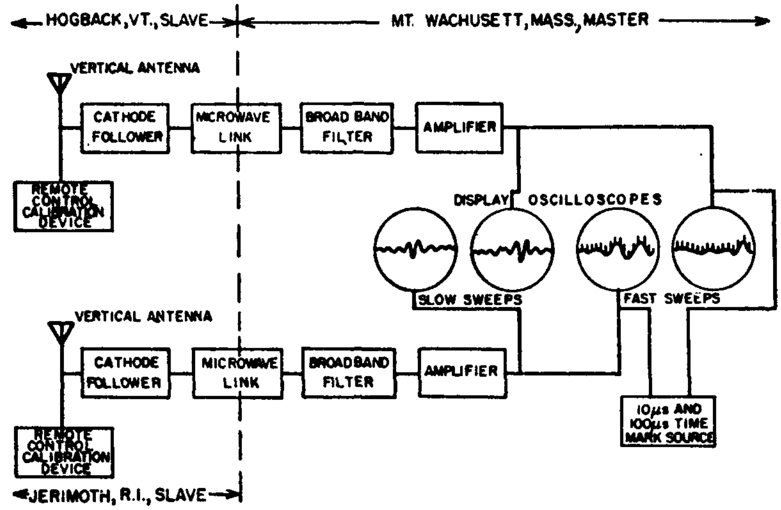

Fig. 25. Block diagram of data channels from slave antenna to master display.

same sferic is shown in Fig. 5.) The rule used in this experiment for phase measurement was to match the peaks of the first half-cycle appearing clearly defined in both of the 200-μsec sweeps. In practice the tracings were on translucent paper and could be slid back and forth with respect to each other until the match was obtained. In matching the peaks, approximately 20 μsec of the traces on either side of the peaks were taken into account by eye, so that the phase match was actually a mentally averaged one rather than a simple point match.

The phase match having been decided upon, the corresponding time difference was read by arbitrarily choosing one of the 10-μsec markers near the peak of one trace (the 180-μsec marker, point x, of the Jerimoth trace in Fig. 9), and the corresponding point was marked on the other trace (point x of the Hogback trace in Fig. 9). The time at this point was read by interpolation; for Figure 9, it was 269 μsec. This meant that the Jerimoth display received the signal $269 - 180 = 89$ μsec before the Hogback display, as is indicated by JH $= 89$ μsec in Figure 9. Had the sequence been the other way around it would have been indicated as HJ $= 89$ μsec. For purposes of record, the tracings of the 200-μsec sweeps for all sferics analyzed are given in Figures 10 through 16, in which the corresponding peaks have been aligned at the indicated match points. (The assignment of numbers to the marker pips as shown in Fig. 9 was arbitrarily adopted for convenience and in no way affects the results.) The first long marker to appear in the sweep was designated as 100 μsec, and the second long marker as 200 μsec. The amplitude scales for the wave forms in Figures 10 through 16 are ar-

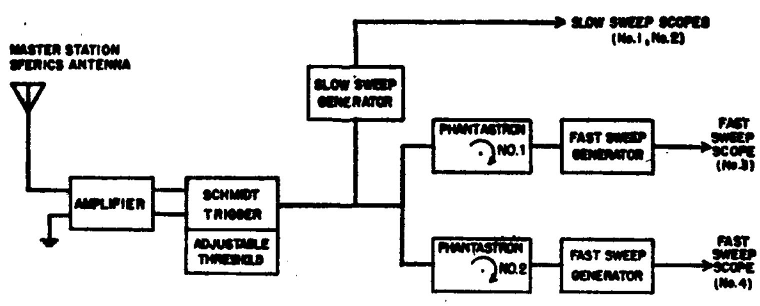

Fig. 26. Block diagram for sweeps (master station only).

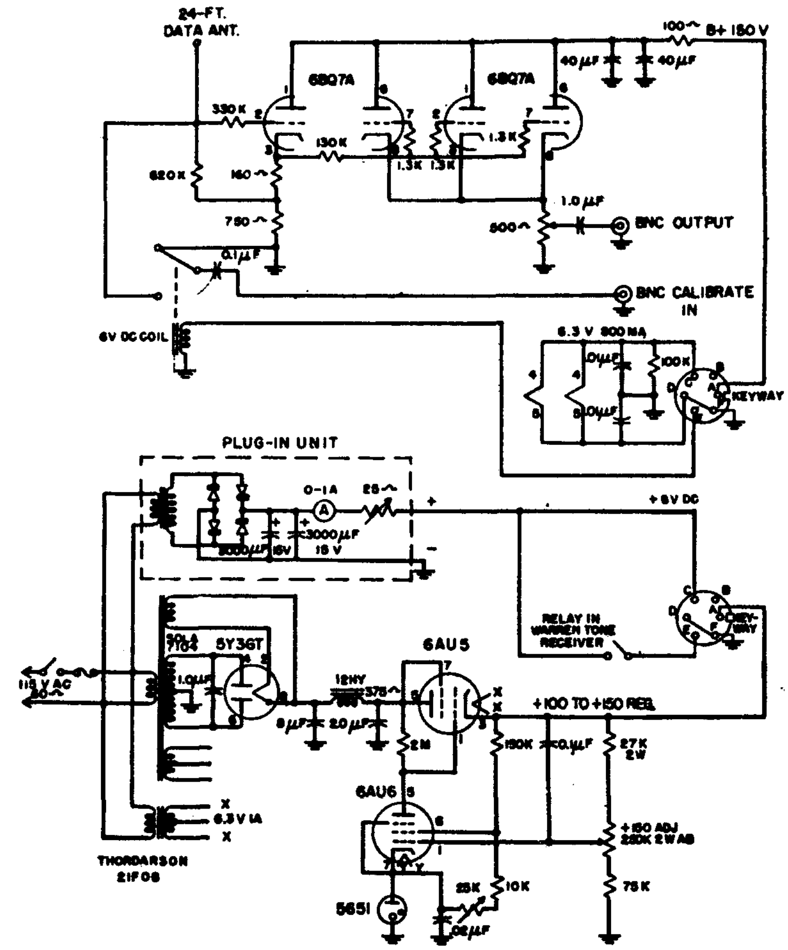

Fig. 27. Cathode follower and power supply.

bitrary, since the individual receiving antennas had not been calibrated. Measurements of the same sferics at the near-by Bedford Laboratory, however, indicated center-to-peak field strengths averaging about 150 mv/m.

The data for each sferic, including the perpendicular error, are given in Table 1. In accordance with the measured round-trip microwave delays as described in Appendix A, the phase difference at the master was converted to phase difference at the slaves by subtracting 45 μsec from a JH reading or adding 45 μsec to an HJ reading. The data as summarized in Table 1 indicate a 'bias error' of 0.3 nautical mile south, which is not significantly different from zero. The 'scatter' error has an average absolute value of 31 nautical miles, which, at a range of 3000 nautical miles, corresponds to a bearing deviation of about 0.6°. This error is a combination of the errors of both the BMO net and the AFCRC net. The number of sferics falling in various 10-mile intervals of error is shown in the bar graph of Figure 17, which indicates a reasonably 'normal' distribution.

Conclusion and comments. In the course of making the phase matches, the impression was obtained that much of the error is due to the display instrumentation, particularly the method of time-mark injection, and the quality of the photographic film recorded, both of which can be improved.

During the runs, equipment troubles of one kind or another caused the greater part of the loss of data. The second greatest cause of data

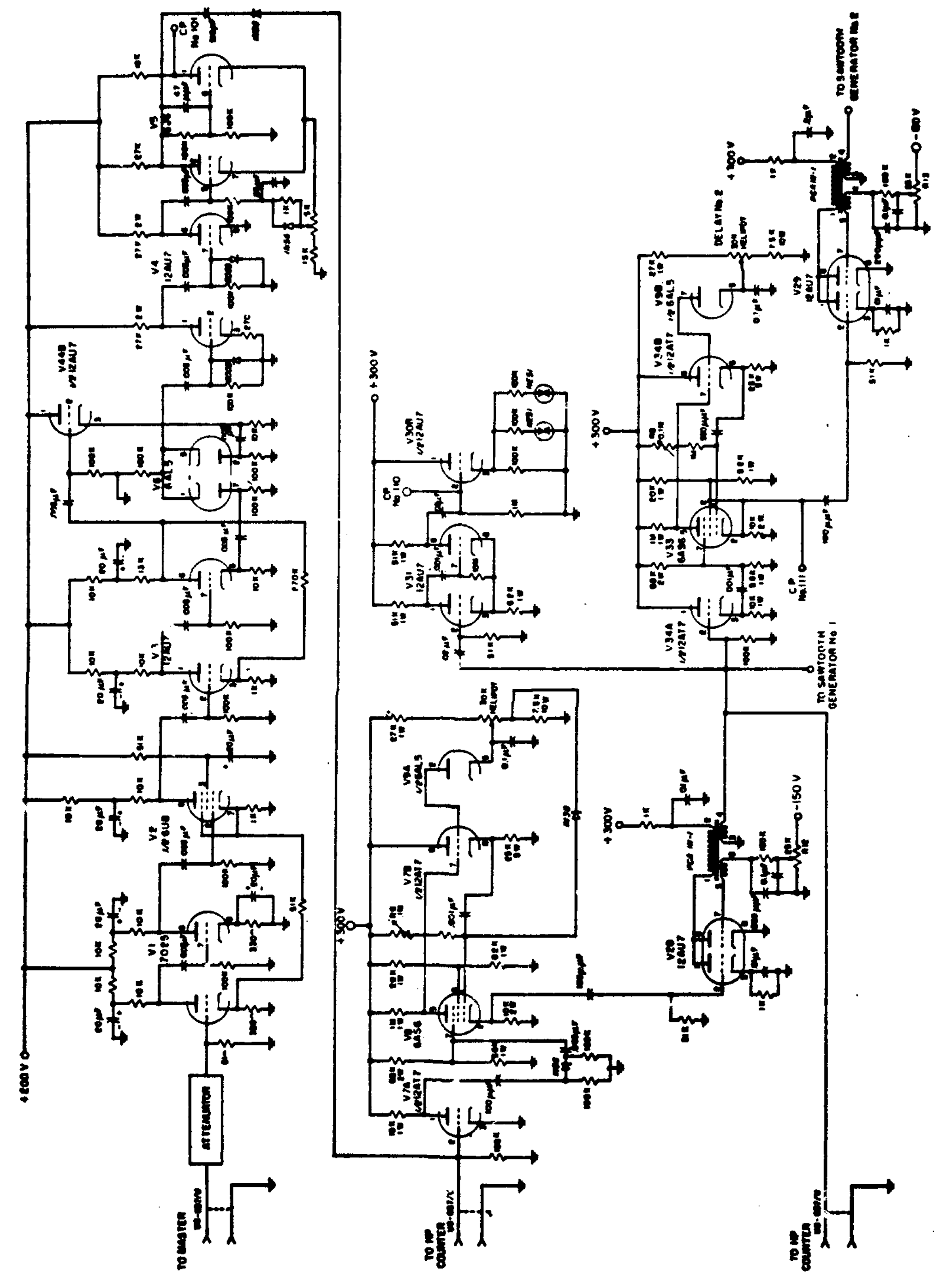

Fig. 28. Master trigger circuit.

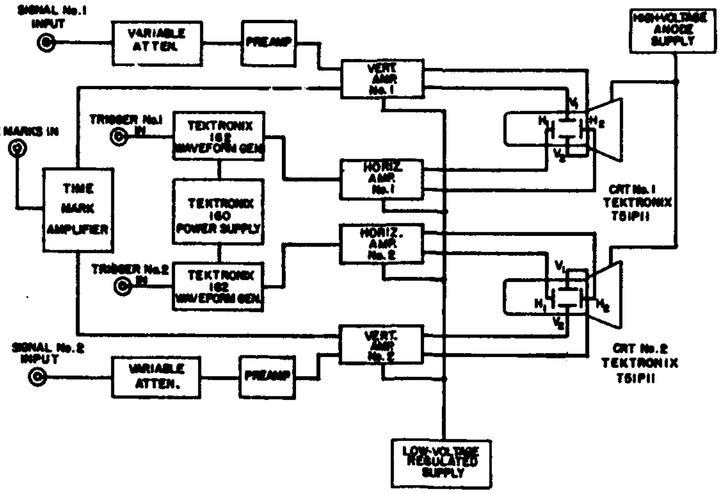

Fig. 29. Block diagram of one set of dual scope data display units.

loss was failure to record the HF beeps clearly; they could often be heard and recognized by ear, but recognition of their recorded envelopes on the film record was much more difficult. Usually, loss of a single beep meant loss of the whole group of six sferics, since their identification was no longer certain. During the operating period there were two intervals of HF blackout (August 14–18 and 20–26), for which no identifications were possible at all, although apparently sferics were being received as usual.

All the runs described were made when the North Atlantic propagation path was entirely in daylight. To determine whether the same or similar results can be obtained at other times of day and other seasons of the year will require more prolonged and more comprehensive experiments. If the accuracy of 30 miles in 3000 obtained in this one experiment is consistently possible, it would appear that two hyperbolic DF stations, one in northeastern United States and one in Alaska, could give sferic fixes over large portions of both Europe and North America.

Appendix A. Instrumentation

Data link equipment. The geometric layout of the slaves and the master is shown in Figure 1. All stations are on elevated locations to ensure line-of-sight paths for the microwave relay links. In order to clear near-by trees and terrain the microwave antennas were placed on upright scaffold-type towers. Figures 18 and 19 are exterior and interior views of a typical slave station (Derry, N. H.). Figures 20, 21, and 22 show the exterior and interior of the master station at Mt. Wachusett. The master station has three parabolic receiving antennas, one directed at each slave. All the microwave antennas are 6 feet in diameter.

The microwave equipment is the commercially available Raytheon KTR 1000A, which operates at about 7200 Mc/s. The individual transmitters are tunable within limits, thus avoiding any possibility of interference with one another. The KTR 1000A is an FM system that radiates 1 watt and provides a video bandwidth of 6 Mc/s. A block diagram of the equipment is shown in Figure 23.

The over-all transmission delay beween the video-input and video-output terminals (Fig. 23) is determined by a round-trip transmission measurement. For this a portable microwave link is used to transmit a sharp pulse from the master to a slave, where the pulse is fed directly into the permanent link to complete the round-trip circuit back to the master, as shown in Figure 24. At the master station the outgoing sharp pulse is also fed to one of the fast-sweep display scopes. Also at the master the receiver of the permanent link is fed into a second fast-sweep display scope. These scopes sweep continuously with time marks on them, and the display is photographed so that the time differ-

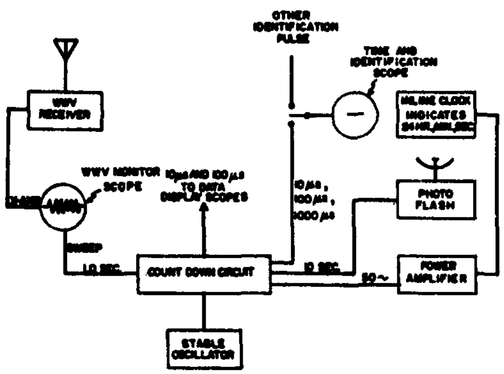

Fig. 30. Timing circuits.

ence between the original pulse and the round-trip pulse can be measured on the film. The one-way transmission time is obtained by dividing the round-trip time by 2.

From these measurements, correcting for slight differences in equipment, the delays from slave antenna to display scope were found to be as follows: Hogback to Mt. Wachusett, 284.1 μsec; Jerimoth to Mt. Wachusett, 239.2 μsec.

Data channels. The antennas used for receiving sferics consist of vertical whips 24 feet long. For reasons of convenience they are currently attached to the microwave towers (see Figs. 18 and 20). The block diagram of Figure 25 traces the signal from the antennas to the oscilloscope display. The over-all frequency response is essentially flat from 5 to 35 kc/s, and the 3-db points are 4 and 45 kc/s. Through remote-control tone-link from the master station, an oscillator located at each of the slave stations can be caused to inject a nominal 10-kc/s signal into the data channel, for testing and calibration purposes.

Sweep circuits. The purpose of the sweep circuits is to provide sweeps of the desired speeds, starting at just the right time to display the waveforms of the incoming pulses, particularly their beginnings; see Figure 4. The block diagram for accomplishing this is shown in Figure 26. When the signal from the antenna exceeds an (adjustable) threshold value (positive or negative) the Schmidt trigger is actuated, thus starting the slow-sweep generator and initiating the phantastrons, which subsequently trigger the two fast sweeps. The phantastron delays are adjustable so that their fast sweeps can be made to occur at the desired instants, depending on which slaves are used and the direction of the sferics. The schematic diagrams for the laboratory-constructed circuits are given in Figures 27 and 28; Figure 29 is a block diagram of the display-scope units.

Timing circuits. The microsecond time required for the precision phase matching is provided by a General Radio type 1101-A master oscillator at the master station. Standard count-down circuits provide the 10- and 100-μsec markers for injection into the data-display scopes.

Coarse time markers for sferic identification can be fed to the (small) time and identification scope shown in Figure 6. In the transatlantic experiment the HF beep from Dunstable was displayed as a horizontal deflection, transverse to the film motion, giving marks of the kind shown in Figure 5. For other purposes it may be desirable to record world time on the film.

To accomplish this, the master oscillator phase is adjusted to synchronize with the received WWV standard time transmissions by means of a monitor scope, as indicated in Figure 30. Count-down circuits then provide 10-, 100-, and 1000-msec markers which are fed to the time and identification scope. In order to register still larger intervals of time a 50-cps electric clock set to world time is driven by an amplified 50-cps voltage from the count-down circuits. At 10-second intervals a flasher unit illuminates the clock face so that its image registers on the film. A more complicated alternative system using electronically flashed numeral-

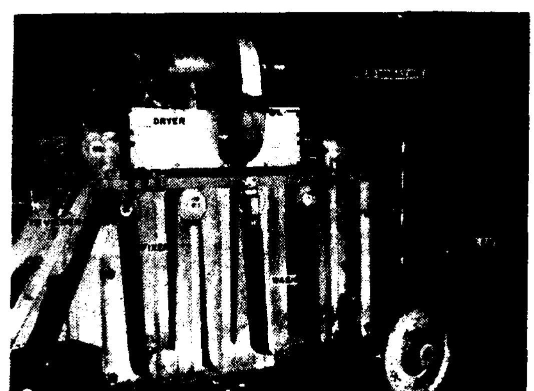

Fig. 31. Photographic system.

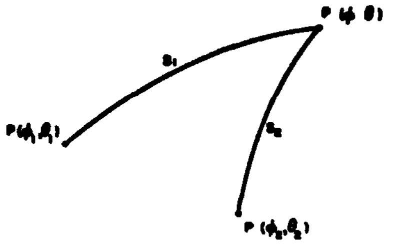

Fig. 32. Points on an oblate sphere.

shaped neon tubes (below the scopes in Fig. 22) for indicating time was used with only indifferent success.

Photographic system. The photographic system (see Fig. 31), containing a camera and a monobath rapid processor, was laboratory constructed. Since film emerges from the processor dry it may be passed directly through a projector for analysis or wound on a take-up reel for later study as was done in the transatlantic sferics runs.

The film is normally driven through the camera processor at about 0.7 in./sec, but other speeds in the range from 0.1 in./sec to 4 ft/sec may be used. At 0.7 in./sec the processed film is available for projection about 4 minutes after the exposure. Dupoint 931 film and Mauer monobath solution have been used with an f 4 lens setting with satisfactory results.

Appendix B. Calculation of a Hyperbolic Grid on an Oblate Earth

A hyperbolic grid on an oblate sphere is determined as follows: Given two points P_1 and P_2 (Fig. 32) on the surface of an oblate sphere (major axis $2a$, minor axis $2b$) with small eccentricity, the problem is to determine the locus of points P_0 on the sphere such that $S_{10} - S_{20}$ [or equivalently $(S_{10} - S_{20})/a$] is a given constant C.

The distances S_{10}, S_{20} are geodesics and are approximated on an oblate sphere of small eccentricity by passing a plane through the center of the oblate sphere and the two points P_0, P_1 or P_0, P_2, and taking the intersection of this plane with the oblate sphere as the geodesic. This procedure produces (Urbano, unpublished note, Geodetic distance on an oblate earth) the following formulas that have been programed for the AFCRC computer. In order to determine $(\phi_0\theta_0)$ for given C it is necessary to solve the equation

$$F(\phi) = 0 = \frac{S_{10} - S_{20}}{a} - C$$

First θ_0 and a first approximation ϕ_0' to ϕ_0 are chosen and $F(\phi_0')$ is calculated. Iteration by the method of regula falsi gives ϕ_0. The relevant formulas for determining the distance S_{12} along the intersection between two points (ϕ_1, θ_1), $(\phi_2\theta_2)$ are:

$$e_{12} = \sqrt{1 - (h_{12}/a)^2}$$

$$h_{12}^2 = \frac{a^2 b^2}{b^2 \cos^2 i + a^2 \sin^2 i}$$

$$\cos S_{12}' = \sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(\theta_2 - \theta_1)$$

$$\sin u = \frac{\cos\phi_2 \sin(\theta_2 - \theta_1)}{\sin S_{12}'}$$

$$\cos i = \cos\phi_1 \sin u$$

$$\tan\alpha = \frac{\tan\phi_1}{\cos u}$$

$$\beta = S_{12}' + \alpha$$

$$\tan\Phi_1 = (a/h_{12}) \tan\alpha$$

$$\tan\Phi_2 = (a/h_{12}) \tan\beta$$

$$\frac{S_{12}}{a} = \int_{\Phi_1}^{\Phi_2} \sqrt{1 - e_{12}^2 \sin^2\phi}\, d\phi$$

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AFCRC personnel are responsible for the concept, design, original construction, and testing of the time-difference net. Under Air Force contract, AVCO Corporation made certain equipment modifications, set up the equipment in its present locations, and assisted us in making the runs.

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HYPERBOLIC DIRECTION FINDING WITH SFERICS OF TRANSATLANTIC ORIGIN, by E. A. Lewis, et al. April 1962. 27 pp. incl. illus, tables. AFCRL-62-178 Unclassified report

The described AFCRC experimental 'hyperbolic direction finder' consists of an array of sferic receivers in the New England area, connected by wide-band data links so that microsecond differences in pulse arrival time can be measured. The hyperbolic directions can be determined from the time differences. In a series of coordinated runs, individual sferics originating in western Europe were observed by both the New England net and the sferics net of the British Meteorological Office. The 3MO furnished the geographic coordinates of the lightning strokes so that measurements of position could be compared. Tabulated results for 150 sferics show an average absolute deviation from the mean of only 31 nautical miles.

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